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Agronomic Analysis of the Replacement of Conventional Agricultural Water Supply by Desalinated Seawater as an Adaptive Strategy to Water Scarcity in South-Eastern Spain

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Abstract: Climate change is affecting water resources in south-eastern Spain, and this mainly affects irrigated agriculture. In this context, seawater desalination is an adaptive strategy that has provided increasing water allotments to agriculture for the last decade, to replace decreasing conventional resources. Farmers are concerned about the agronomic effects of this substitution and its economic consequences. This study focuses on the potential agronomic impacts of the progressive replacement of the irrigation water from the Tagus–Segura transfer (TST) with desalinated seawater (DSW) on the main crops of south-eastern Spain. To that end, five main agronomic concerns were selected and analyzed under three water supply scenarios using increasing rates of DSW (0, 50, and 100%). The results indicated that, in addition to other economic or environmental considerations, sufficiently relevant agronomic aspects exist that need to be considered when replacing the TST supply with DSW. This study evidences the risks of phytotoxicity and soil alkalinization, due to the increase in boron concentration and the imbalance between monovalent and divalent cations in the DSW, respectively, and also a slight increase in the cost of fertilizers. In addition, the irrigation water salinity effect on production and total irrigation requirements was negligible, as both water sources present sufficiently low salinity. The detrimental effects were mitigated under a partial replacement scenario, so the blended use of DSW with conventional resources seems the most recommendable option for its agricultural management, rather than irrigating with DSW alone.

Keywords: desalination; agriculture resilience; water quality; fertilization requirements; boron phytotoxicity; soil alkalinization

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1. Introduction

Ensuring food security through the development of irrigated agriculture is the main driver of the growing water demand worldwide. This is increasing the pressure on water resources and leading to imbalances between resources and demands in water-scarce regions [1]. The consequences of this include more frequent disputes among users, as more water is often allocated to high-priority sectors at the expense of agriculture [2]. Moreover, global climate change forecasts predict that available water resources will diminish, thereby exacerbating water scarcity around the world, especially under arid and semi-arid climates [3]. This unfavorable scenario is putting pressure on agriculture in the Mediterranean area, where current or future demand for irrigation cannot be met by relying solely on conventional water sources [4]. Therefore, new agricultural water supply options such as seawater desalination must be explored in order to enhance the resilience of irrigated agriculture to climate change [5,6].

Large-scale allocation of desalinated seawater (DSW) has already been implemented to sustain irrigated agriculture in some Mediterranean regions such as Israel [7] and south-eastern Spain [8]. Its adoption as an alternative agricultural water supply is also being considered in other regions worldwide [9–14], with this trend being expected to continue and even intensify in the future. In this context of growing interest in seawater desalination for irrigation, new studies analyzing its feasibility according to agronomic considerations are required.

Previous studies have raised important questions about the repercussions produced by the substitution of traditional water resources with DSW. The most relevant bibliography on the topic [15–22] has shown both its advantages and disadvantages, but all are in agreement that DSW is becoming a technically and economically viable solution for high-yield agriculture in coastal areas. Focusing on the agronomic questions, DSW is characterized by its low salinity and imbalances in its chemical composition in relation to other natural water sources. Its low salinity may boost the crop yield, especially when replacing marginal waters, and hence may also avoid soil degradation. Furthermore, irrigating with low-salinity water results in a reduction in total irrigation needs since the salt leaching requirements can be reduced compared with higher salinity waters. On the downside, the singular composition of DSW, with its very low concentration of essential nutrients, such as calcium, magnesium, and sulfate, implies that higher amounts of fertilizers are required to avoid adverse impacts on crop yield, with the corresponding rise in farm operational costs. Finally, the incorporation of DSW into crop irrigation poses risks of plant phytotoxicity and soil alkalinization, due to the relatively high concentration of boron and the imbalance between monovalent and divalent cations in the DSW, respectively.

A good study case of large-scale agricultural allocation of DSW is the Segura River basin (SRB), located in south-eastern Spain (Figure 1). This basin is one of the most water-stressed areas in the Mediterranean region, with a persistent deficit of water resources, which mainly affects the over 250,000 ha of irrigated agricultural land [7]. Among its available resources is the Tagus–Segura transfer (TST), which enables an external water delivery from the neighboring Tagus basin in central Spain. The TST was planned to deliver approximately one-third of the SRB's water resources. Nevertheless, expectations have not been met because of the gradual decreasing trend in the transferred volumes. That trend is mainly related to climate change impacts and, more recently, to increases in the ecological flows in the Tagus basin, exacerbating the regional water deficit [23,24]. To address this problematic situation, the Spanish Government opted for the implementation of large-scale seawater desalination plants (SWDPs) to provide a new water resource amid increasing tension and rivalry for the scarce water resources [25]. Therefore, seawater desalination was adopted as a supply-side measure to guarantee the urban supply and foster irrigated agriculture resilience in the SRB. Consequently, DSW has progressively replaced the TST supply for irrigated agriculture, and will be further intensified in the future, as detailed in the official basin hydrological planning [26]. This replacement scenario particularly affects the irrigation districts served by the TST (almost 100,000 ha of farmland, Figure 1), where the physicochemical characteristics of irrigation water are suffering frequent changes that may have significant agronomic impacts. These impacts may sometimes prove beneficial, but also detrimental on occasions. In several surveys, farmers have expressed particular concern about the higher price and some of the aforementioned agronomic questions in relation with their perceptions regarding the use of DSW for irrigation in south-eastern Spain [27,28].

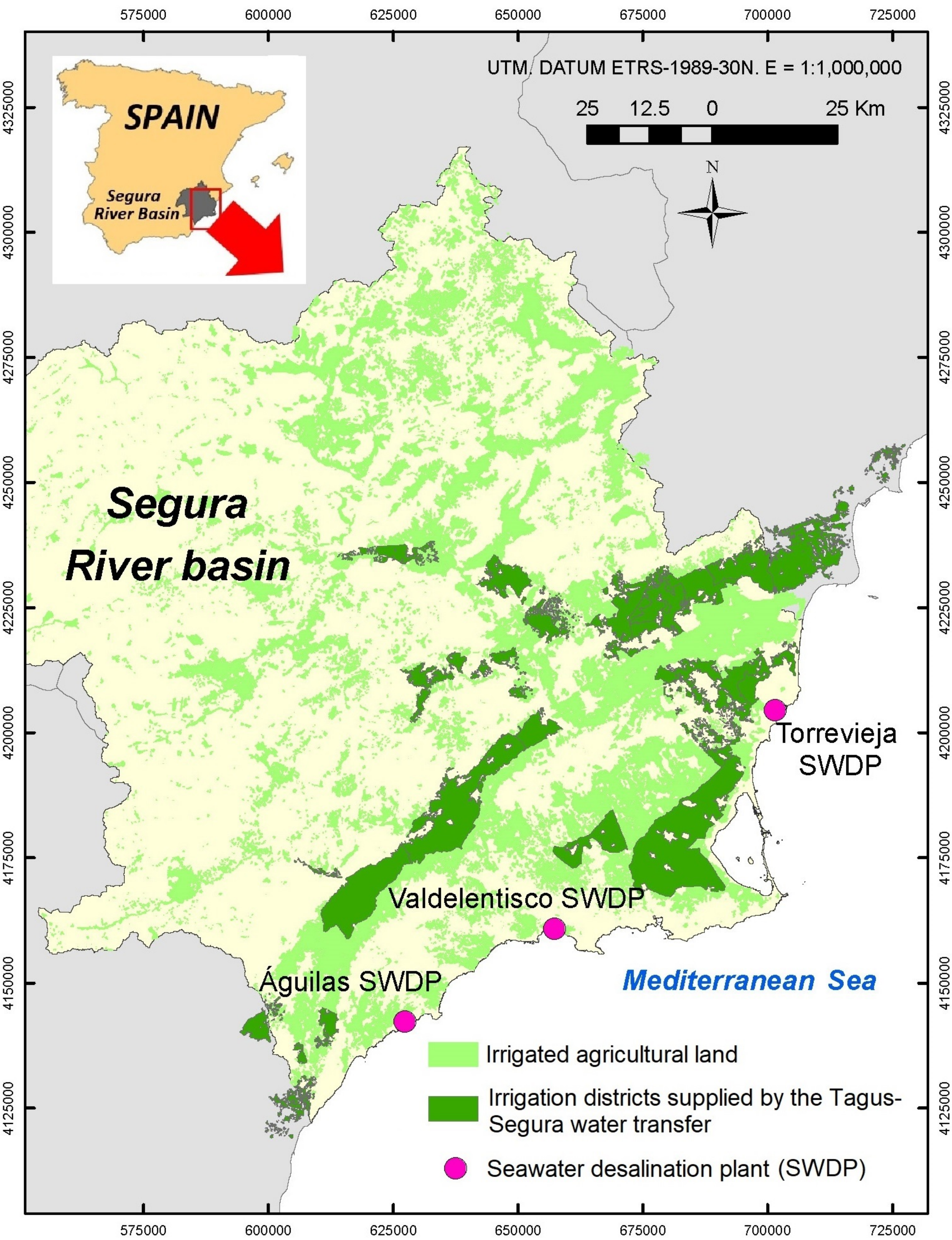

Figure 1. Location of the Segura River basin and the irrigation districts supplied by the Tagus-Segura water transfer in south-eastern Spain. The public seawater desalination plants suppling agriculture in the study area are also presented.

The aim of the present study is to analyze the relevance of the agronomic impacts resulting from the gradual replacement of the TST supply with DSW on the most important crops of the irrigation districts that have TST water allocation in the SRB. The impacts considered were those pointed out in the main scientific literature on the subject: (1) the effect of water salinity on agricultural productivity; (2) the effect of water salinity on salt leaching requirements and, subsequently, on total irrigation needs; (3) the effect of the low concentration of essential ions in DSW on fertilizer requirements and, consequently, on fertilizer costs; (4) the risk of phytotoxicity due to the relative high boron content in DSW; and (5) the risk of soil alkalinization due to the imbalance between monovalent cations (Na^{+}) and divalent cations (Ca^{2+} and Mg^{2+}) in DSW. These questions were analyzed under water supply scenarios with a gradual replacement of TST water by DSW (0%, 50%, and 100%). Based on these scenarios, the methodological approaches defined below were applied for the selected crops under the agronomic conditions of the study area. Calculations were made using data from official sources (regional and national public organizations) and scientific publications.

The study shows that, from the irrigator's perspective, there are sufficiently relevant agronomic aspects which should be considered when substituting TST water with DSW, so such supplies should not be considered equivalent. The regional and holistic perspective in the agronomic analysis of the gradual incorporation of DSW into irrigated agriculture represents the main novelty of the study.

2. Materials and Methods

2.1. Evolution and Foreseeable Trend of TST and DSW Supplies in the Study Area

The surface area of the SRB covers 19,025 km^2, of which 52.1% is agricultural land, and 13.8% is irrigated land. The irrigated horticultural sector has a prominent role in the regional economy in terms of production, employment, and exports [26]. According to the latest official estimate [26], the available water resources in the SRB amount to an average of 1510 Mm^3/y. This figure includes surface and groundwater resources (756 Mm^3/y), external transferred water (TST, 312 Mm^3/y), DSW (305 Mm^3/y), and reclaimed water (147 Mm^3/y). That volume is not enough to satisfy the water demand in the SRB, which is estimated to be an average of 1697 Mm^3/y. This amount includes irrigated agriculture (1476 Mm^3/y), domestic supply (200 Mm^3/ y), and industrial uses (21 Mm^3/y). Additionally, 94 Mm^3/y of the total demand covers uses located outside the SRB, but which are satisfied with own resources. These figures show that the basin system suffers from an average water deficit of approximately 281 Mm^3/y. This persistent water deficit mainly affects the irrigation area supplied by the TST, which constitutes our study area, currently covering 95,599 net irrigated hectares (Figure 1).

In 1979, the external TST allotment was incorporated into the SRB hydrological system. The total transferable resources were initially estimated at 600 Mm^3/y, of which 421 would correspond to the irrigation districts supplied by the TST, according to Law 52/1980, of 16 October 1980, regulating the exploitation of the TST. However, after more than 40 years of operation, it should be noted that the TST allotment has progressively fallen, mainly due to climate change effects in the headwaters of the Tagus River. The average volume transferred to date has been 295 Mm^3/y, of which 197 Mm^3/y correspond to the irrigation districts supplied by the TST [26]. Moreover, this decline in the transferable resources is expected to intensify over the next years, due to a programmed progressive increase in the ecological flows of the Tagus River laid out in the hydrological planning, as well as an intensification in the climate change effects. In this regard, the foreseeable transferable resources to the irrigation districts supplied by the TST for the planning horizons 2027 and 2039 will amount to 119 and 82 Mm^3/y, respectively.

As a result of this reduction in the volumes transferred over those initially planned, the irrigation districts supplied by the TST have suffered a permanent water deficit, with its consequent socioeconomic and environmental impacts. This deficit should have been reduced in previous planning cycles with the progressive concession of new non-conventional water resources from water reclamation and, especially, seawater desalination. To that end, the Spanish government enacted the scheme *AGUA* in 2004 [7], which had the objective of deploying 21 large-scale SWDPs on the Mediterranean coast, with a global production capacity of 1063 Mm^3/y for agricultural, urban, and leisure uses [25,29]. As a result, the SRB is home to three public large-sized SWDPs, which are mainly dedicated to the irrigation districts supplied by the TST: Torrevieja, Águilas, and Valdelentisco (Figure 1). The current hydrological planning cycle proposes an increase in the agricultural supply from these SWDPs "up to the maximum that their civil works will allow" to compensate for the foreseeable reduction in the volumes that can be transferred to the irrigation districts supplied by the TST.

Figure 2 summarizes the evolution and foreseeable trend of transfers to the irrigation districts supplied by the TST, as well as the evolution and planned DSW agricultural supply from Torrevieja, Águilas, and Valdelentisco SWDPs. These data highlight the increasing role of DSW to compensate decreasing TST allotments in the study area, justifying the high interest in analyzing the agronomic impacts of the progressive replacement of these water sources.

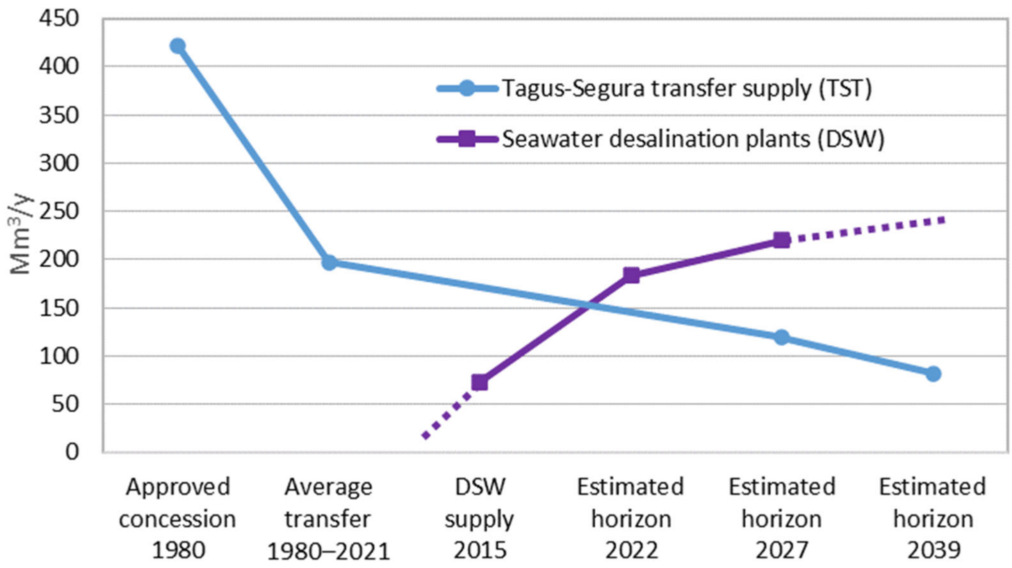

Figure 2. Evolution and foreseeable trend of transfers to the irrigation districts supplied by the TST, and DSW agricultural supply from public SWDPs.

2.2. Water Sources and Supply Scenarios

The source of the water is the determining factor when distinguishing the considered scenarios, since it implies different physicochemical properties and, consequently, different agronomic effects. Three water supply scenarios were considered, with a progressive replacement of TST water with DSW:

- TST scenario. This was the situation prior to the implementation of seawater desalination for crop irrigation in the study area and corresponds to a 100% supply from the TST.
- MIX scenario. This represents the partial replacement (50%) of the TST supply by DSW and corresponds to a situation very similar to the current one in the study area.
- DSW scenario. This represents the total replacement of the TST supply by DSW and corresponds to a hypothetical future situation without the TST.

Table 1 gives the physicochemical properties of irrigation water for each water source and supply scenario, as well as the data sources. For the DSW scenario, the properties considered were the average values of the water analyses provided for Torrevieja, Águilas, and Valdelentisco SWDPs by the public company in charge of managing them (Acuamed), except for the boron content, where the variation range was considered. The MIX scenario uses averaged values of the TST and DSW scenarios.

Table 1. Physicochemical characteristics of the water sources and supply scenarios considered in the study.

Parameter	Torrevieja SWDP [1]	Águilas SWDP [1]	Valdelentisco SWDP [1]	DSW Scenario	MIX Scenario	TST Scenario [2]
pH	9.1	9.3	8.9	9.1	8.7	8.2
EC (dS/m)	0.163	0.452	0.732	0.449	0.584	0.718
Ca^{2+} (mg/L)	12.9	10.5	11.9	11.7	58.9	106
Mg^{2+} (mg/L)	<1	2.5	7.4	3.6	16.7	29.8
Na^{+} (mg/L)	22	74	132	76.0	45.2	14.4
B^{3+} (mg/L)	0.39	0.67	0.80	0.39–0.80	0.20–0.40	<0.05
Cl^{-} (mg/L)	35	119	215	123	74.6	26.1
CO_3H^{-} (mg/L)	18	30	18	22.0	98.0	174
$CO_3{}^{2-}$ (mg/L)	9.8	<5	5.4	7.6	4	<5
SAR	2.3	5	7	4.8	2.5	0.3

EC: electrical conductivity; SAR: sodium adsorption ratio. [1] Data from the physicochemical analyses provided by Acuamed, the public company that oversees the SWDPs' management, in June 2023. [2] Data from the physicochemical analysis of a water sample taken in July 2023.

2.3. Crop Selection

The crops selected for the analysis were those that covered the largest irrigated surface areas for the study area in 2020 [30]. Ten crops were selected, which can be organized into the following groups: outdoor vegetables (broccoli, lettuce, artichoke, and melon); citrus trees (orange, lemon, and mandarin); and non-citrus trees (almond, apricot, and peach). The selected crops represented 80.1%, 97.4%, and 87.6% of the outdoor vegetables, citrus trees, and non-citrus trees in the study area, respectively. The proportions corresponding to the irrigation districts supplied by the TST were 32.9%, 39.2%, and 18.1% of their total area for outdoor vegetables, citrus trees, and non-citrus trees, respectively. Summarizing, the ten selected crops represented a total of 90.2% of the crops grown in the study area.

2.4. Agronomic Impacts

2.4.1. Effect of Water Salinity on Crop Yield

Crop productivity is limited by the salinity of irrigation water, a question that has been extensively analyzed in the literature [31,32]. Some examples of the beneficial effect of irrigation water salinity reduction on crop productivity when replacing traditional agricultural supplies with DSW have been reported for different crops in Spain [33] and Israel [34]. In the FAO technical manual Water Quality for Agriculture [35], the relative yield of a crop (Y_r, %), is calculated as the yield obtained under salinity conditions divided by the yield obtained in the absence of salinity, estimated as a function of soil salinity, measured as the electric conductivity in the soil saturation extract (EC_e):

$$Y_r = 100 - b\,(EC_e - a) \tag{1}$$

where a is the threshold of the electrical conductivity in the soil saturation extract over which the crop starts to lose yield due to salinity, and b is the slope of the relative yield function. The value of EC_e is generally calculated as being 1.5 times the value of the electrical conductivity of the irrigation water (EC_w) [35]. Table 2 shows the values of parameters a and b in Equation (1) for the selected crops, taken from the specialized literature [32,35].

Table 2. Parameters *a* and *b* of the relative yield function and soil saturation extract electric conductivity producing a 100% yield decrease ($maxEC_e$) for the selected crops.

Crop	*a* (EC_e Threshold) [1] dS/m	*b* (Slope) [1] %	$maxEC_e$ [1] dS/m
Artichoke	6.1	11.5	14.8
Broccoli	2.8	9.2	14
Lettuce	1.3	13	9
Melon	1.0	8.4	12.9
Lemon	1.5	12.8	9.3
Mandarin	1.7	13.1	8
Orange	1.7	13.1	8
Apricot	1.6	24	5.8
Peach	1.7	21	6.5
Almond	1.5	19	6.8

[1] Data from [32,35].

2.4.2. Effect of Water Salinity on Total Irrigation Requirements

The total irrigation requirements of a crop (N_t, m^3/ha) are greater than net requirements (N_n), since more water is needed to counterbalance the losses caused by the growing conditions [36]. The effect of water salinity on N_t accounts for the fact that as water salinity decreases, the salt leaching fraction also decreases and, accordingly, N_t is lower. Therefore, a reduction in N_t could be expected when a higher rate of DSW is considered in the scenarios of our case study. The N_t for each crop and scenario was calculated according to the FAO technical manual Guidelines for Predicting Crop Water Requirements [36], and leaving aside other local considerations regarding soil texture or irrigation system uniformity. They were calculated as:

$$N_t = N_n/(1 - LF) \tag{2}$$

$$LF = EC_w/(2 \cdot maxEC_e) \tag{3}$$

where LF is the leaching fraction and $maxEC_e$ refers to the soil saturation extract electric conductivity producing a 100% decrease in crop yield; these values were obtained from the literature [32,35], and are given in Table 2.

2.4.3. Effect of the Low Concentration of Essential Nutrients on the Cost of Fertilizers

The replacement of traditional water sources with DSW could expose the plants to a lack of essential nutrients, thereby affecting yield quality and quantity; this has been reported for crops such as tomatoes, basil, and flowers in Israel [16,17]. As shown in Table 1, DSW is characterized by a very low concentration of essential nutrients such as calcium and magnesium. However, these nutrients are abundant in TST water and generally meet the crop needs [37], so they are not usually considered, or only have a secondary role in the fertilization programs applied in the study area. When there is a total (DSW scenario) or partial (MIX scenario) replacement of TST water by DSW, fertilization programs must be adapted to increase the calcium and magnesium inputs, which generally implies an increase in the cost of fertilizers.

To assess the importance of this effect, the self-developed optimization algorithm of Irriblend-DSW [38] was applied. This model calculates the optimal combination (type and quantity) of fertilizers to satisfy the total nutrient requirements of each crop at the lowest economic cost, considering the physicochemical characteristics of the water supply for each of the scenarios (Table 1). The algorithm is coded in *Python 3* and uses the *optimize.minimize* function of the *SciPy* library for constrained minimization with the Sequential Least SQuares Programming to minimize the fertilization cost when given a set of available fertilizers (composition and price) and a pre-set water blend of DSW with other resources, considering a set of constraints (salinity, nutrients, pH). We have already used the algorithm successfully in the study area [37], and have improved it for optimizing fertilization with a mix of water from different origins and qualities [38]. Since one of the model outputs is the cost of fertilizers, this information was taken to assess the effect of the low concentration of essential nutrients for each crop and scenario.

The nutrient requirements considered for the target production are those published by the "Ministry of Agriculture, Fisheries and Food" of Spain in the "Studies of Costs and Income of Farms" [39] and the "Agricultural Information Service of Murcia" [40] for the selected crops in the study area. The commercial fertilizer database includes products usually available in the region and was obtained from the values provided by three supplying companies.

2.4.4. Effect on Boron Phytotoxicity Risk

The coming years will see a significant increase in the concentration of boron in the irrigation water of the study area, due to its higher concentration in DSW than in the TST (Table 1). This circumstance, together with the management of crops sensitive to boron phytotoxicity (citrus and stone fruit trees) and the presence of semi-arid climatic conditions, justifies the growing concern about this risk in the study area [27].

Boron is an essential trace element for the growth, development, and productivity of horticultural crops. Its availability in soil and irrigation water is an important factor in agricultural production [41]. Small amounts of boron are necessary for plant growth, but signs of toxicity may appear when plants are exposed to higher values [42]. The boron in TST water is below 0.05 mg/L, so supplemental fertilizer inputs through micronutrient complexes are usually necessary for proper crop development in the study area. However, DSW is characterized by significantly higher boron levels, with values of around 1 mg/L being common. These concentrations exceed crop requirements and could even increase the soil boron content in the medium to long term, triggering toxicity problems and leading to diminished yields in sensitive crops, as was found in Israel with boron levels of 0.6, 1.2, and 2.0 mg/L [16]. Increasing values of boron may even produce more critical effects such as the permanent wilting of the crop [43].

The definition of boron tolerance limits in irrigation water for different crops is a complex process involving a huge experimental effort. Several factors, such as crop variety, soil type, climatic conditions, and irrigation management practices, play an important role and can condition the results obtained [44]. We considered the boron tolerance limits proposed by Wilcox [45], which were included in an FAO technical manual (Water Quality for Agriculture [35]); its use has become widespread as the main reference for the tolerance of agricultural crops to boron. Table 3 shows the threshold of boron that produces phytotoxicity for the selected crops as per that manual. The effect of the progressive replacement of the TST supply by DSW on the boron phytotoxicity risk was assessed by comparing values in Table 3 with boron values expected under the considered scenarios (Table 1).

Table 3. Threshold of boron producing phytotoxicity in the selected crops.

Crop	Boron Concentration (mg/L)
Artichoke	2–4
Broccoli	2–4
Lettuce	2–4
Melon	2–4
Lemon	<0.50
Mandarin	0.50–0.75
Orange	0.50–0.75
Apricot	0.50–0.75
Peach	0.50–0.75
Almond	([1])

Data based on [35]. [1] Data for almond trees were not found in the bibliography.

It should be noted that a boron level of around 1 mg/L is a characteristic value for SWDPs equipped with a reverse osmosis single-pass technology. However, when DSW is mainly used for agricultural irrigation, double-pass reverse osmosis systems can be implemented to guarantee lower boron content [46]. This is the case for the Torrevieja and Águilas SWDPs, which have technology that can limit boron in DSW to below 0.5 mg/L (Table 1). Valdelentisco SWDP produces with a single-pass system and, consequently, boron usually ranges between 0.80 and 1 mg/L.

2.4.5. Effect on Soil Alkalinization Risk

The high concentration of monovalent cations (Na^+) compared to divalent cations (Ca^{2+} and Mg^{2+}) in irrigation water can result in the dispersion of clays, damaging the soil structure and consequently affecting its physical properties. This phenomenon is known as soil alkalinization or soil sodicity and highly affects crop yield [47,48].

The reverse osmosis process of seawater results in a product with a relatively high concentration of Na^+ and practically zero concentrations of Ca^{2+} and Mg^{2+}, known as osmosed water. Under these conditions, osmosed water would pose a severe risk of soil alkalinization, in addition to its very low hardness, no buffering capacity, and a high corrosive capacity [15,16]. To minimize these issues, osmosed water receives remineralization post-treatments prior to distribution, in which the Ca^{2+} concentration is increased, thereby partially decreasing the risk of soil alkalinization. Depending on the remineralization technology and intensity, the resulting physicochemical characteristics of DSW can vary considerably, as shown in Table 1, as can the consequent risk of soil alkalinization.

The risk of soil alkalinization in the medium and long term depends on the EC_w and the value of the quantitative indicator sodium adsorption ratio (SAR), which is calculated from the concentration of Na^+, Ca^{2+}, and Mg^{2+} (mmol/L) in irrigation water with the following expression [35]:

$$SAR = [Na^+]/(([Ca^{2+}] + [Mg^{2+}])/2)^{0.5} \quad (4)$$

With the knowledge of the EC_w and SAR under each water supply or considered scenario, the graph shown in Section 3.5 enables their risk of soil alkalinization to be assessed.

3. Results and Discussion

3.1. Effect of Water Salinity on Crop Yield

Table 1 shows a slight decrease in the EC_w from the TST scenario (0.718 dS/m) to the MIX scenario (0.584 dS/m) and the DSW scenario (0.449 dS/m). Although all cases presented adequate salinity values from an agronomic perspective, a favorable impact on crop yield could be expected as the proportion of DSW increases in the considered scenarios. Relative yield (Y_r, %) for each crop and scenario was 100%, except for melon (99.5%).

The results indicate that there was no such favorable effect on productivity due to a decrease in salinity when the TST supply was replaced by DSW for all the crops considered at whichever substitution rate was used (MIX or DSW scenarios). This is because EC_w in the TST scenario was already low enough to give rise to the characteristic crop productivity in the absence of salinity. In other words, the value of the threshold from which crops started to lose production due to salinity (a) was already higher than the value of $1.5 \cdot EC_w$ in all the scenarios for all crops considered, except for melon (Table 2). In the case of melon, the parameter a presented a value of 1.0 dS/m, slightly lower than $1.5 \cdot EC_w$ = 1.08 dS/m in the TST scenario, which minimally affected its productivity (Y_r = 99.5%, i.e., a decrease in melon production of 0.5% in the TST scenario). Therefore, the impact of water salinity on melon crop productivity in the TST scenario can be considered negligible compared to the general absence of effect on productivity for the rest of the crops when the TST water was partially (MIX scenario) or totally (DSW scenario) replaced by DSW.

3.2. Effect of Water Salinity on Total Irrigation Requirements

The decrease in EC_w when moving from the TST scenario to the MIX or DSW scenarios was not relevant since all scenarios presented low EC_w values (Table 1). In general, for the study area, it can be stated that for waters with EC_w below 1–1.2 dS/m, it is not necessary to apply the salt leaching fraction (*LF*, %). This is due to the fact that percolation at depth related to the emission uniformity in the irrigation system, and/or the precipitation itself when occurring in significant quantities, already perform the salt leaching function. Therefore, a decrease in total irrigation requirements (N_t) when replacing TST supply with DSW was not expected, despite a slight decrease in EC_w as the percentage of DSW increased (Table 1). The stated low relevance of *LF* in comparison with other water losses at depth is contrasted below.

Table 4 shows the *LF* in irrigation water to guarantee the agronomic sustainability of the soil for each crop and scenario. The *LF* presented low (outdoor vegetables) to moderate values (woody crops), whereas their variation between scenarios was small in all cases. As expected, a slight decrease in *LF* was observed when moving from the TST scenario to the MIX scenario (from 0.9% in artichoke to 2.3% in apricot), or to the DSW scenario (from 1.8% in artichoke to 4.6% in apricot).

Table 4. Leaching factor (*LF*, %) for each crop and scenario considered.

Crop	TST Scenario	MIX Scenario	DSW Scenario
Artichoke	4.9	3.9	3.0
Broccoli	5.1	4.2	3.2
Lettuce	8.0	6.5	5.0
Melon	5.6	4.5	3.5
Lemon	7.7	6.3	4.8
Mandarin	9.0	7.3	5.6
Orange	9.0	7.3	5.6
Apricot	12.4	10.1	7.7
Peach	11.0	9.0	6.9
Almond	10.6	8.6	6.6

To convert the relative figures in Table 4 into absolute values (m^3/ha), the N_t for the selected crops is presented in Table 5. This corresponds to the figures published by the "Ministry of Agriculture, Fisheries and Food" of Spain in the "Studies of Costs and Income of Farms" [39] in the study area. From those N_t values, the absolute values of leaching requirements (Equation (3)) and their differences with respect to the TST scenario were also calculated in Table 5.

Table 5. Total irrigation requirements (N_t, m^3/ha) and leaching requirements (m^3/ha) for each crop and scenario considered.

Crop	N_t (m^3/ha)	Leaching Requirements (m^3/ha)		
		TST Scenario	MIX Scenario	DSW Scenario
Artichoke	10,570	513	417 (−96)	321 (−192)
Broccoli	6967	357	290 (−67)	223 (−134)
Lettuce	4926	393	319 (−74)	246 (−147)
Melon	4500	250	204 (−47)	157 (−94)
Lemon	5930	458	372 (−86)	286 (−172)
Mandarin	6608	593	482 (−111)	371 (−222)
Orange	4993	448	364 (−84)	280 (−168)
Apricot	5643	699	568 (−131)	437 (−262)
Peach	5776	638	519 (−120)	399 (−239)
Almond	3806	402	327 (−75)	251 (−151)

The leaching requirements in the TST scenario ranged from 250 m^3/ha for melon to 699 m^3/ha for apricot, with an average value of 475 m^3/ha. This average value decreased to 386 m^3/ha when switching to the MIX scenario, and to 297 m^3/ha when switching to the DSW scenario. In general, these leaching requirements and their variation between scenarios are very small amounts compared to the 362 mm of annual rainfall in the SRB [26], a figure that exceeds 300 mm in most of the irrigation districts supplied by the TST. Thus, there are additional water contributions to irrigation in excess of 3000 m^3/ha in the study area (1 mm = 10 m^3/ha); many such contributions are not used by crops as they percolate beyond the root zone, becoming part of the salt leaching requirements.

Specifically, two main circumstances in the study area allowed us to consider an important part of the precipitation as leaching requirements. First, rainfall is scarce, but it is characterized by heavy events, in which an important part of the rainfall infiltrates deeper than the root zone of the crops. Second, 35% of the irrigated plots in the study area are dedicated to outdoor horticulture, where one or two crop cycles are usually carried out annually, with the land remaining uncultivated for several months of the year, during which time rainfall can also be considered part of the leaching requirements.

In summary, the EC_w in the three scenarios was low and, consequently, the salt leaching requirements were reduced. They were therefore satisfied by the part of the precipitation that infiltrates and percolates deeper than the root zone of the crops, and/or the lack of emission uniformity in the irrigation system, with no differences in N_t being attributable because of the differences in salinity in the scenarios considered. In agreement with this analysis, many authors recommend disregarding leaching requirements when they represent less than 10% of N_t [31,35,49].

3.3. Effect of the Low Concentration of Essential Nutrients on the Cost of Fertilizers

Table 6 shows the cost of fertilizers required to meet the nutritional needs of each of the crops and scenarios considered, calculated with the fertilizer optimization model indicated in the methodology. As expected, the use of DSW caused an increment in the required nutrient inputs, with a consequent increase in the cost of fertilizers for all crops. This increase was slight when moving from the TST scenario to the MIX scenario (below 100 €/ha); it represented less than 1% of the operating costs for all crops. However, the increase grew from 2 to 4 times when moving from the TST scenario to the DSW scenario, representing between 1 and 4% of the crop operating costs.

Table 6. Cost of fertilizers (€/ha) for each crop and scenario considered. The relative (%) and absolute (€/ha) variation in the cost of fertilizers between scenarios is presented in brackets.

Crop	TST Scenario	MIX Scenario	DSW Scenario
Artichoke	1412	1532 (8.5%; +120)	1835 (30.0%; +423)
Broccoli	1384	1463 (5.7%; +79)	1695 (22.5%; +311)
Lettuce	1478	1534 (3.8%; +56)	1657 (12.1%; +179)
Melon	1324	1375 (3.9%; +51)	1730 (30.7%; +406)
Lemon	1018	1085 (6.6%; +67)	1153 (13.3%; +135)
Mandarin	1032	1106 (7.2%; +74)	1182 (14.5%; +150)
Orange	1202	1259 (4.7%; +57)	1316 (9.5%; +114)
Apricot	910	973 (6.9%; +63)	1038 (14.1%; +128)
Peach	1263	1329 (5.2%; +66)	1394 (10.4%; +131)
Almond	385	428 (11.2%; +43)	507 (31.7%; +122)

The relative variation between scenarios (Table 6) indicates that the increase in the cost of fertilizers was more noticeable for outdoor vegetables than for woody crops, which is attributed to the higher intensity of fertilization programs in vegetables due to their seasonal growing cycle. Again, the increase in the total replacement scenario (DSW scenario) was far more pronounced than in the partial replacement scenario (MIX scenario), indicating that the scarcity of nutrients in DSW was mostly mitigated when it was used in combination with TST water, whose content of nutrients such as Ca^{2+} and Mg^{2+} usually exceeded outdoor crops' requirements.

It should be noted that in the study area, all of the selected crops are grown on soil with outdoor production systems. Nevertheless, when more intensive cropping systems are considered, as is the case of hydroponic production systems in greenhouses, the impact of the lack of nutrients in DSW on the costs of fertilizers can become significantly more important than those presented in Table 6. This is the case of soilless bell pepper in the southernmost irrigation districts supplied by the TST, where increases of 3150 €/ha and 886 €/ha on the cost of fertilizers were estimated for the total, and partial (50%) substitutions of the conventional water supply by DSW, respectively [37]. A similar fertilizer cost increase (3500 $/ha) was reported in Israel for greenhouse bell pepper cultivation with a hydroponic system when fully replacing the local conventional water supply with DSW [17]. Therefore, the increase in the cost of fertilizers was relatively low for the crops analyzed under soil cultivation systems in the study area but could be relevant for more intensive cultivation systems.

3.4. Effect on Boron Phytotoxicity Risk

Figure 3 shows the threshold range of boron content that produces phytotoxicity for the selected crops together (Table 3) and the range of boron expected in irrigation water under the scenarios considered (Table 1). It was observed that horticultural crops (artichoke, broccoli, lettuce, and melon) did not accumulate phytotoxic concentrations of boron during their short production cycles for any scenario. On the contrary, most woody crops (mandarin, orange, apricot, and peach) accumulate boron in their tissues over time, and hence would be particularly sensitive to irrigation under DSW scenario. Specifically, these woody crops would be negatively affected by water from Valdelentisco SWDP (boron ≈ 0.8 mg/L), but would not be sensitive to water from Torrevieja SWDP (boron < 0.4 mg/L). Águilas SWDP presented intermediate values (boron = 0.67 mg/L) that could also affect these crops. Finally, in the case of lemon trees, which are the most sensitive crops, it could even be affected in the MIX scenario when DSW came from Valdelentisco SWDP.

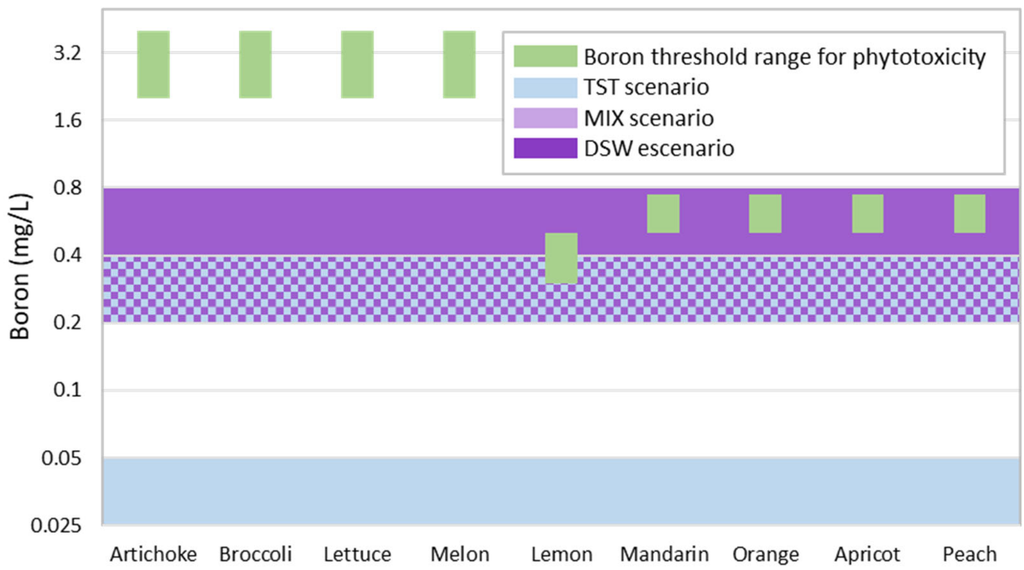

Figure 3. Threshold range of boron producing phytotoxicity in selected crops, and range of boron expected in irrigation water under the scenarios considered.

These results indicate that there was an evident risk of boron phytotoxicity in most woody crops when irrigating from the Valdelentisco and Águilas SWDP for the DSW scenario. The DSW from Torrevieja SWDP could also pose a risk for lemon trees. This risk disappeared for all woody crops, except lemon, for the MIX scenario, where boron would decrease to 0.20 mg/L in crops irrigated from Torrevieja SWDP, to 0.34 when irrigated from Águilas SWDP, and to 0.40 mg/L for the Valdelentisco SWDP.

Therefore, there are two alternative recommendations to reduce the boron phytotoxicity risk in the study area. First, the agricultural DSW supply from Valdelentisco SWDP should receive an additional reverse osmosis stage to reduce its boron to levels similar to those from the Torrevieja SWDP. Second, the combined use with other water sources with low boron, such as TST water in the MIX scenario, would allow boron concentrations to be below 0.40 mg/L in the worst case. Otherwise, farmers with sensitive crops would have to implement on-farm boron reduction facilities, requiring significant investment and operating costs [50].

3.5. Effect on Soil Alkalinization Risk

Figure 4 presents the mid-long term potential risk of soil alkalinization for the considered scenarios, as well as for the DSW produced in the Torrevieja, Águilas, and Valdelentisco SWDPs, considering the values of the analyses in Table 1. The intensity of remineralization processes in the SWDP of the study area resulted in SAR values between 2.3 and 7 $(mmol/L)^{0.5}$, with the mean value being 4.8 $(mmol/L)^{0.5}$. These differences among SWDPs, together with the difference in EC_w, led to different soil alkalinization risks: Torrevieja SWDP presented very low salinity and SAR, resulting in a severe risk of soil alkalinization; Águilas SWDP had somewhat higher salinity and SAR values, resulting in a slight to moderate risk; whilst Valdelentisco SWDP had the highest salinity and SAR values, resulting in a lower risk than the other SWDPs. Therefore, given that the Ca^{2+} concentration in DSW increases significantly in the remineralization process, the intensity of reverse osmosis (one or two stages) and remineralization at the SWDPs affects the risk of soil alkalinization of their supplies. Therefore, it is advisable to set minimum levels of this element in DSW to control that risk.

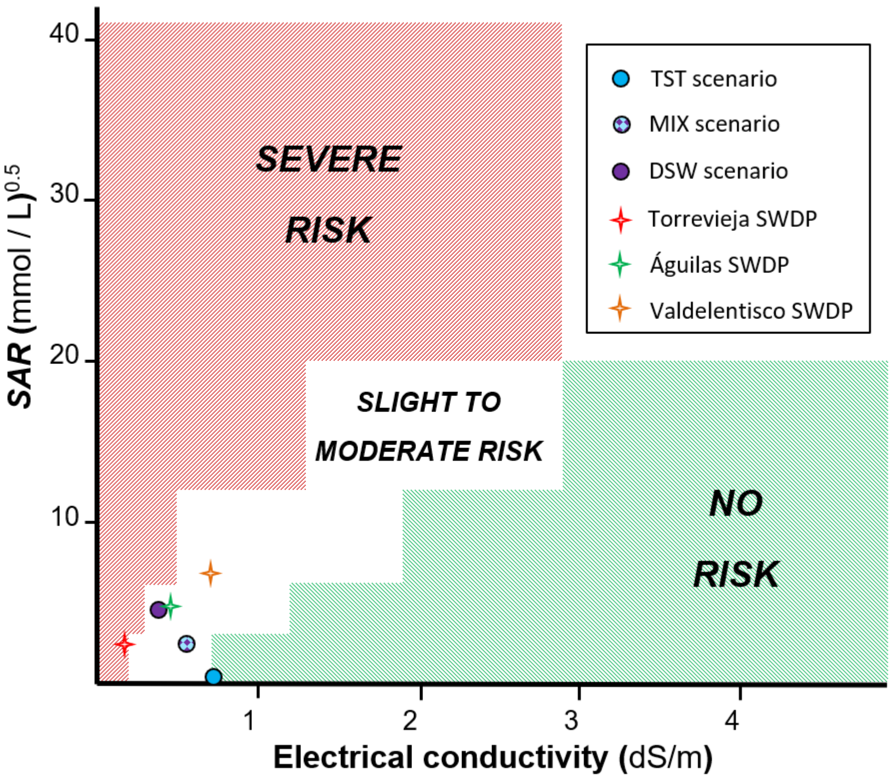

Figure 4. Mid- to long-term potential risk of soil alkalinization for the considered scenarios and Torrevieja, Águilas, and Valdelentisco SWDPs, evaluated using the sodium adsorption ratio (*SAR*) and the electrical conductivity (EC_w) of irrigation water.

When analyzing the mean values for the scenarios, Figure 4 shows a slight to moderate risk for the DSW scenario. This result contrasts with the representation of irrigation water in the TST scenario, which was in the no-risk zone, while the MIX scenario also presented a slight to moderate soil alkalinization risk, albeit much closer to the no-risk zone than the DSW scenario.

In general, it can be stated that the risk of soil alkalinization is moderate to high if only DSW is applied to irrigation and that the risk decreases when it is managed jointly with other surface resources, as in the MIX scenario. Moreover, it should be noted that, as analyzed in Section 3.3, farmers will apply supplementary amounts of Ca^{2+} and Mg^{2+} with the fertilization, which would slightly increase the EC_w value and would clearly reduce the *SAR*. This will result in a more favorable mid-long term potential soil alkalinization risk of the MIX and DSW scenarios in Figure 4.

In addition, it should be noted that currently, the quality of DSW for agricultural use is not directly regulated, unlike reclaimed water, the other main source of non-conventional water resources [51]. Consequently, farmers have no guarantee regarding DSW physicochemical characteristics and homogeneity over time. The lack of regulation of DSW supplies could result in insufficient remineralization processes or supplies with a high *SAR* or boron concentration, which would be detrimental to farmers. Accordingly, our recommendation is that certain agronomic characteristics of DSW should be regulated, such as its electrical conductivity, boron concentration, calcium and magnesium concentration, and *SAR*; this which would largely minimize the cost of fertilizer overruns and the risks of boron phytotoxicity and soil alkalinization. In that way, as in the case of any marketable product, providing a definition of primary DSW physicochemical characteristics would represent a guarantee for both the producer and the consumer, as well as for the environment. The current dynamics of continuous growth in the agricultural DSW supply further justifies the need for this specific regulation.

4. Conclusions

Seawater desalination is expected to play an increasing role to support sustainable agriculture and to be an efficient adaptive strategy to foster irrigated agriculture resilience as climate change impacts intensify. The irrigation districts supplied by the TST in southeastern Spain are a clear example of this, where DSW is compensating the progressive downward trend of the conventional supply. The study novelty lies in the fact that the agronomic impacts of the progressive replacement of traditional irrigation supplies by DSW are assessed from a holistic and regional perspective. Our results are particularly relevant to farmers, irrigation districts and regional water managers, for decision making in water-scarce coastal regions.

The results indicate that, aside from other economic and environmental considerations, several relevant agronomic aspects should be considered when replacing the TST supply by DSW in the study area. This substitution does not present any benefit with respect to the effect of irrigation water salinity on crop productivity, or on total irrigation requirements, since both water sources present sufficiently low salinity values to avoid this type of impact. On the contrary, the substitution produces a slight increase in the cost of fertilizers, which becomes more relevant when total replacement occurs (DSW scenario) than for the partial one (MIX scenario). Moreover, the total replacement can also lead to phytotoxicity problems in woody crops (lemon, mandarin, orange, apricot, and peach), due to the increase in the boron concentration in DSW, as well as to soil alkalinization, caused by the imbalance between the concentration of monovalent and divalent cations in DSW. These agronomic risks are effectively mitigated under the MIX scenario, where the lower boron content and the high concentration of divalent cations in TST water counterbalance DSW chemical singularities. Both agronomic risks could also be controlled by regulating the physicochemical characteristics of agricultural DSW supplies.

Our research also highlights that the combined use of TST and DSW is the most recommendable management option for agricultural use since the unfavorable impacts identified are mostly mitigated in the MIX scenario. In agreement with this statement, several authors have concluded that blending DSW with other conventional waters is in most cases the best approach to mitigate possible agronomic and economic impacts or risks, stressing the benefits of the integrated planning and management of DSW with other available water resources in agriculture [17,38]. In this sense, regulating the physicochemical characteristics of the agricultural supply of DSW would also favor the planning of its joint management with that of other water resources available in each irrigation district or farming area, contributing to mitigating agronomic problems and risks.

This study can be considered as a first approximation to the issues under study. It should be interpreted with caution, as it involves general scenarios that are representative of the great diversity in the study area rather than particular farm cases. The insights from this study could be useful for the assessment of the feasibility of integrating DSW to support agriculture in other regions where DSW is being considered to support irrigated agriculture as an adaptive strategy to climate change.

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